THE ZODIACAL LIGHT AS OBSERVED WITH THE CLEMENTINE STARTRACKER CAMERAS: CALIBRATION AND IMAGE ANALYSIS PROCEDURES. Zook, H. A.[1], Cooper, B. L.[2], and Potter, A. E.[1], [1]NASA Johnson Space Center, MC SN3, Houston, TX 77058, zook@snmail.jsc.nasa.gov, potter@snmail.jsc.nasa.gov, [2]Cooper Research, 1611 Dakota St., League City, TX 77573-7231, bcooper@ghgcorp.com.

The zodiacal light, due to sunlight reflected off of interplanetary dust grains, is a measure of their spatial density as a function of heliocentric distance and latitude. We have developed procedures to photometrically correct the brightness variations in the Clementine Corona and Zodiacal Light (CZL) photographs to true image brightnesses. The processing steps follow generally along the path described by Berry[1]; however, there are additional processing steps involved for the Clementine images. Careful corrections are necessary because of the dimness of the features that we wish to observe[2].

1) Removal of thermal background electrons. The Star Tracker and UV/Vis CCD cameras were operated without active cooling, and so their temperatures varied somewhat depending on where the Clementine spacecraft was in its orbit. This caused the thermal electrons per CCD pixel per frame (usually several thousand) to vary with time. To a first approximation we can use a formula developed at Lawrence Livermore to subtract off the thermal electrons. When we also have a part of the Moon in the picture that is not illuminated by either the Sun or the Earth, we can further require that the formula be adjusted to give a "null" result on the dark Moon. (Starlight on the Moon should result in significantly less than one digital unit.)

2) Streak removal. Because the Star Tracker camera did not have a shutter, the CCD was continuously exposed. Consequently, additional CCD photon recording--beyond the primary exposure time--occurred during the time of CCD "read out". Each pixel records the local time-integrated image intensity at its location in the CCD during the primary exposure time, T. However, each "logical" pixel also records image intensities at all other pixel locations along a CCD column for the shorter time, τ, that it takes to read out each row of the CCD. If there is a bright region in the image, then pixels that are at column positions above and below that bright spot not only record their own primary image location for time T, but each element is also exposed to the bright region for a lesser time, τ. This causes a "streak" in the resulting image.

If we let M_{ij} equal the measured pixel response at each i, j (row, column) position, and A_{ij} equal the "actual" pixel response that would occur due only to exposure T at that same position, then we must solve n simultaneous equations, where n = 576 (the number of rows in the Star Tracker CCD), to obtain the A_{ij}. The elements of the resulting matrix equation are given by

$$M_{ij} = A_{ij} + e\sum_{\substack{l=1 \\ l\neq j}}^{n} A_{lj}$$

where $e = \tau/T$. The inverse of this matrix is obtained analytically and the matrix elements are given by

$$A_{ij} = BM_{ij} - C\sum_{\substack{l=1 \\ l\neq j}}^{n} M_{lj}$$

$$B = \frac{1-(n-2)e}{[1+(n-1)e](1-e)}$$

where

$$C = \frac{e}{[1+(n-1)e](1-e)} .$$

and

This method of streak removal only works when image pixels are not "saturated". In those cases, another method of streak removal can be used. This involves obtaining an "average background" row for those rows in the darkest part of the image, and subtracting it, line by line, from the entire image. When the very dark Moon (unlit by Earth shine) covers several rows of the image, suitable background rows may be taken from that area, since these pixels have much less than one digital unit of true image brightness. This procedure also removes the thermal electron background.

3. Flatfield corrections. Each image must be divided by a "flat field image", to derive photometrically accurate maps of the CZL. A flatfield image is obtained by photographing a field of uniform brightness with the flight camera. At Zook's request, Research Support Instruments, Inc. (RSI), in support of the Naval

Research Lab (NRL) and under tight time constraints, attempted to obtain flat field Star Tracker images in the "integrating sphere" at NRL. However, the uniform field of the integrating sphere was too bright for even the shortest allowable exposure times for the Star Tracker camera. RSI got around that problem by putting a neutral density 2 filter (ND2) in front of the camera's light baffle. This solved the over-exposure problem but raised another: the light that goes obliquely through a neutral density filter is absorbed more than light that strikes the filter at normal incidence; also, more light is reflected from the filter surfaces at oblique incidence. Figure 1 shows the corner brightening that occurs with the uncorrected flatfield.

We have carried out laboratory measurements, at a variety of incidence angles, of light transmission through an ND2 filter supplied by RSI that is identical to the one used in the NRL integrating sphere calibrations. With these measurements we are adjusting, as best we can, the flatfield images supplied by RSI for the flight camera. The division of the Clementine flight images by the "flatfield" is done only after thermal background and streak removal are completed on both the flight images and the flatfield images.

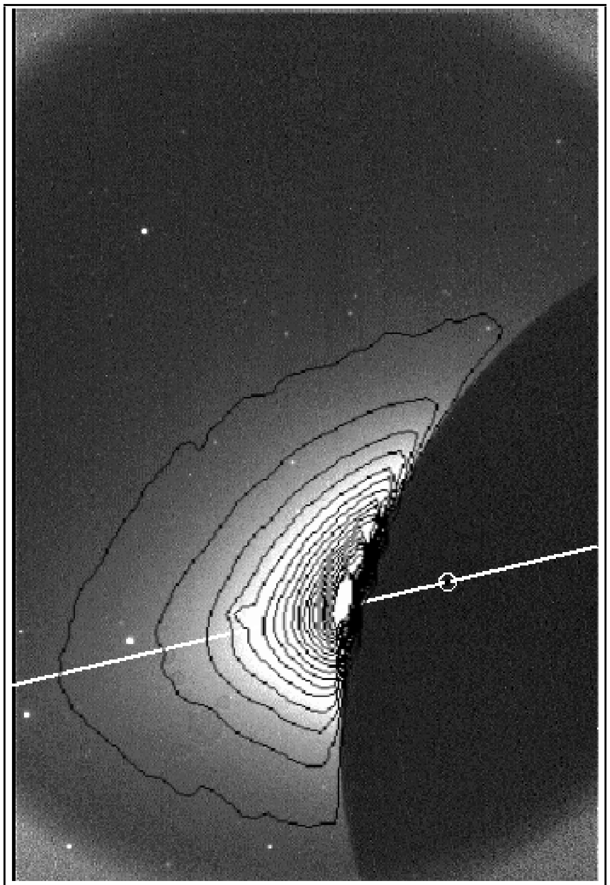

Figure 1. Clementine Startracker image showing CZL extending beyond the lunar limb. The sun is occulted by the Moon, and its position is marked by the circle at right. The plane of the ecliptic is shown by the white line. The contour lines represent isophotes (lines of equal brightness) of the CZL. The brightening at the corners is caused by incorrect flatfielding (see text for details).

4. Calibration of images to absolute brightness. In order to know absolutely how much CZL is represented in each image, it is important to establish a reference by which we can compare any pixel's intensity against a standard. Stars and planets of known magnitude and spectral intensity distribution provide a useful reference for this purpose. Their visual magnitude and spectral type (corrected for extinction) are compared with one another and with the CZL. The yellow to white light of type G stars corresponds to the color of the CZL.

5. Determination of Solar Depression Angle, and Location of Pixel Position of Occulted Sun. In order to make meaningful comparisons of the amount of horizon glow seen in each image, we need to know how far the sun is below the lunar horizon in each case. This can be determined from the starfield pattern and an ephemeris of the Sun’s position.

We can estimate the degree of tilt of the plane of symmetry away from the plane of the ecliptic by comparing an image upon which the plane of the ecliptic has been overlaid, along with an isophote plot of the zodiacal light (Figure 1). The procedure is an improvement on our previous method[3]. There appears to be a slight asymmetry in the shape of the zodiacal light; however, the degree of tilt of the plane of symmetry aligns to within a degree or two of the plane of the ecliptic.

[1] Berry, R. (1994), Image Processing in Astronomy, *Sky & Telescope*, April 1994, pp. 30-36.

[2] Zook, H. A., Potter, A. E., and Cooper, B. (1995), The Lunar Dust Exosphere and Clementine Lunar Horizon Glow. *Abstracts, LPSC XXVI*, 1577-1588.

[3] Cooper, B. L., Zook, H. A., and Potter, A. E., (1996), Clementine Photographs of the Inner Zodiacal Light, in *Physics, Chemistry, and Dynamics of Interplanetary Dust*, A.S.P. Conf. Ser. Vol. 104, pp. 333-336.